ARCTIC SEA AIR INTERACTION including AASERT

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Award No. N0001490J1075 and N000149410791

LONG TERM GOALS

Our long term goal is a quantitative understanding of how the ocean and atmosphere interact in the presence of a sea ice cover, on both local and regional scales. Because the greatest uncertainties in this interaction involve the effects of shortwave radiation on the ice and upper ocean, research is focused on processes that control the vertical distribution, storage, and transport of solar energy within this system. Results from this work should lead to more general and more accurate models for predicting not only the extent and thickness of the arctic ice pack, but also seasonal changes in mixed layer structure and biological activity beneath the ice.

OBJECTIVES

Our objective is the development of a comprehensive model that will accurately predict not only reflection, absorption, and transmission of shortwave radiation by the ice cover under any type of environmental forcing, but also the effects of this energy on the ice and ocean. The principal problem that remains to be solved in this development is the characterization of optical properties of the ice and their evolution with time and temperature. Radiative transfer in sea ice is controlled largely by included inhomogeneities (e.g. brine pockets, vapor bubbles, precipitated salts, and various types of particulates) whose size and distribution depend strongly on ice temperature, depth below the surface, and ice type. Because little is known about the specific distribution or behavior of these inhomogeneities, we plan to observe natural samples of sea ice in the laboratory to obtain detailed information on: (1) the microstructure of different types of sea ice, (2) temperature-dependent changes in the size and number of inclusions, and (3) the effects of such changes on albedo and transmission. These data will be used to test a structural-optical model that explicitly treats the thermal evolution of these inhomogeneities and connects this evolution to optical properties and radiative transfer in the ice.

APPROACH

We have formulated and carried out initial tests of a structural-optical model for sea ice. Despite some uncertainties about the microstructure of the test samples, the model was able to correctly predict relative changes in the albedo and transmissivity of laboratory-grown sea ice between -8 and -35 C where radiative transfer is dominated by precipitated salt crystals present in the brine pockets. There were, however, two significant problems. First, the model was unable to predict the magnitude of the radiation field unless we specified more scatterers than appeared to be present in the ice. A possible explanation for this is that compound inclusions (e.g. air bubbles within brine pockets) produced more scattering than expected. The second problem was that the model did not correctly describe temperature-dependent changes in warmer (>-8 C) ice where

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 1997**	2. REPORT TYPE	3. DATES COVERED **00-00-1997 to 00-00-1997**

4. TITLE AND SUBTITLE **Arctic Sea Air Interaction Including AASERT**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Washington,Department of Atmospheric Sciences,Seattle,WA,98195**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**5**	

optical properties are controlled by complex changes in the shape and number of brine pockets and vapor bubbles. It was clear from these results that we lacked sufficient information about the microstructure of sea ice and about scattering by ensembles of non-spherical inclusions.

To address these issues, we are carrying out a series of laboratory experiments designed to provide more exact data on both structural and optical changes in sea ice. Pairs of identical ice cores, including both first-year and multiyear ice, were collected near Barrow, Alaska and shipped to our laboratory. One core from each pair is used to obtain data on bulk properties such as salinity and density, and to prepare thin sections for structural analysis. Segments cut from the companion core are used for optical measurements. Core segments and thin sections can be observed under a wide range of temperatures in our cold rooms. To analyze optical data from the finite core samples, we have constructed a highly efficient, backward Monte Carlo model that can take into account the cylindrical, 3-dimensional nature of our samples. The model not only computes light losses along core boundaries, but can also predict radiance or irradiance at any position and in any direction in or on its cylindrical domain. With this model, it should be possible to infer inherent optical properties of the sample and to quantify their relationship to the structural properties observed with the thin sections. Results will be incorporated into the structural-optical model, then coupled to a 4-stream, discrete ordinates model to predict the radiation field within and beneath the ice. Comparison of predictions with additional field and laboratory data will provide a rigorous test of the accuracy of the model, particularly when applied to summer sea ice.

ACCOMPLISHMENTS

A very high resolution video system has been designed and constructed to document the microstructure of sea ice. The system consists of a B/W CCD video camera equipped with a Leica Monozoom lens and a 3x objective which provides resolution down to about 1 micron. The video signal goes directly to a frame grabber installed in a Power PC. The signal also goes to a high resolution monitor so that an appropriate scene can be selected and the image properly focused. Software developed at the National Institute of Health was used to capture and process all the imagery. The system has been used to study and record the behavior of numerous samples of first-year sea ice at temperatures between about -2 and -30 C (see Fig. 1). Time-lapse imagery was also obtained during several warming experiments.

Development and testing of the Monte Carlo radiative transfer model has continued. While it can be used to treat standard one-dimensional problems, this model has been designed specifically for analysis of ice core data, radiance data collected in boreholes, or data from any other medium with cylindrical boundaries. The model has been designed to treat both direct and diffuse radiation sources, refraction at all boundaries, scattering from oriented inclusions, and there are virtually no restrictions on the values of single-scattering albedo, optical depth or phase functions that can be used. Vertical variations are represented in the model by horizontally uniform layers. Exhaustive tests of this model have been carried out. Comparison with predictions from a number of multistream, discrete ordinates models over a wide range of one-dimensional cases yielded excellent agreement in all cases where such models are valid. Unlike the multistream models, the Monte Carlo model was able to obtain accurate results even with highly forward-peaked phase functions. The model easily handles situations where the forward asymmetry parameter of the phase function is in excess of 0.99. Tests of 3-dimensional predictions by the model were equally successful, with conservation of energy requirements being satisfied to better than 1%.

Studies of how included sediments and other types of particulates affect radiative transfer in sea ice have been extended. We have now completed a comprehensive series of calculations that detail the effects of particulates on transmitted radiation beneath a first-year sea ice cover. The calculations show that, unlike the albedo, transmission is relatively insensitive to the vertical distribution of particulates but very sensitive to total particulate loading. Results from this work and from the earlier albedo investigation were presented at two scientific conferences. A manuscript describing the complete results has been completed and submitted to the *Journal of Geophysical Research*.

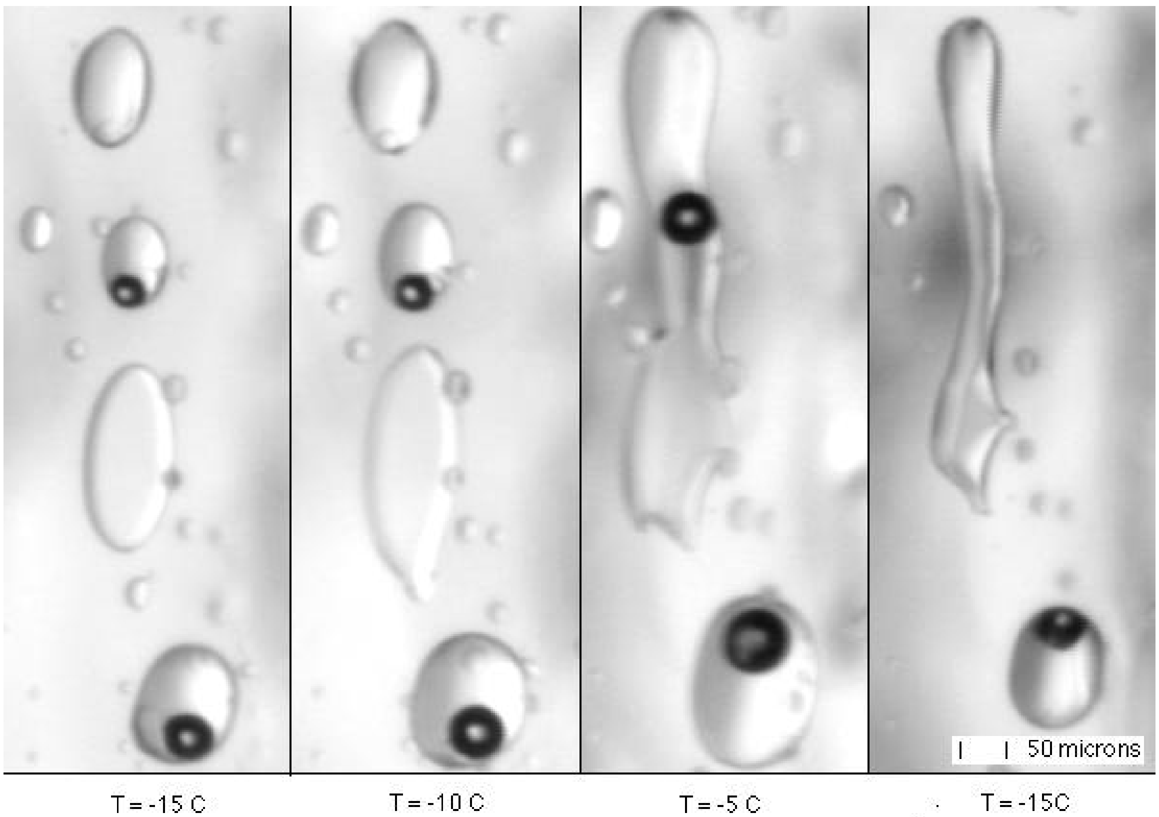

Figure 1. Sequence of medium resolution images showing changes in the microstructure of a first-year sea ice sample as temperature is slowly warmed from -15 C to -5 C, then cooled back to -15 C. Displayed in the images are pockets of brine, some of which contain vapor bubbles that can be distinguished by thick, dark circular rings. Warming causes enlargement and merging of the brine pockets, as well as an increase in the size of the included vapor bubbles. It can be seen, however, that such warming produces irreversible structural changes when the sample is returned to its original temperature.

SCIENTIFIC/TECHNICAL RESULTS

Analysis of the thin section imagery has produced a picture of first-year sea ice that is extremely different than expected. For example, previous observations suggested that there are only about 1-2 brine pockets per mm^3. Our data, when averaged over all the samples, indicate that there are about 35 brine pockets per mm^3 at -15 C and 25 per mm^3 at -5 C. About 70% of these pockets are smaller than 25 microns, the resolution limit of the earlier studies. These smaller pockets account for about a third of the total scattering produced by brine pockets and are thus an important factor that will explicitly need to be taken into account in efforts to model radiative transfer in sea ice.

Our data also indicate that vapor bubbles in sea ice are much more numerous and much smaller than previously believed. Earlier studies reported that there were fewer than 0.1 bubbles per mm^3 and that few if any bubbles were smaller than 100 microns. Our images, on the other hand, show that the number of bubbles averages about 14 per mm^3 with nearly all bubbles being in the 10-50 micron size range. Essentially all the bubbles were found to occur in brine pockets, but not all brine pockets contained vapor bubbles. On average about 40% of the brine pockets contained bubbles, regardless of temperature. It appears from these results that vapor bubbles play a much larger role in determining the optical properties of sea ice than we had expected on the basis of previous studies. We are now in the process of incorporating these results into the structural-optical model to re-examine earlier predictions of albedo and transmission and to evaluate the implications of higher scattering levels within the ice.

Thermal cycling of the ice samples also produced a number of surprises. As expected, warming of the ice caused brine pockets to increase in size. Merging of brine pockets at warmer temperatures caused number densities to decrease by about 30% as the sample was warmed from -15 to -5 C. Figure 1 shows that this merging produces highly non-spherical inclusions which complicate the treatment of scattering at warmer temperatures. Contrary to some theories, we saw no evidence that, upon cooling, elongated brine pockets or tubes separate into multiple smaller inclusions. It appears that warming the ice above -10 C can produce irreversible changes in structure, the size of the changes being directly related to how close the ice gets to the melting point. Most surprising was the apparent absence of vapor bubbles in many of the smaller brine pockets, even when the ice was warmed to -2 C. Whether the vapor was contained in microbubbles too small to detect or whether other processes were at work has yet to be determined. Salt crystals were also visible in some of the brine pockets at lower temperatures. Crystals of mirabilite could occasionally be seen in the bottom of larger brine pockets when temperatures were in the -8 to -22 C range. At colder temperatures, some brine pockets (usually larger ones) appeared very dark due the presence of precipitated hydrohalite crystals. Again, we are not entirely certain why these crystals were visible in some brine pockets and not in others. It may be that some physics associated with the behavior of very small inclusions has been neglected. Additional work is needed to identify the processes responsible.

IMPACT FOR SCIENCE

The high resolution laboratory studies of sea ice microstructure have drastically altered our picture of the number and size distribution of brine pockets and vapor bubbles present within the ice. This knowledge should allow us to develop a much more realistic relationship between ice structure and optical properties that will directly benefit the structural-optical model. The importance of the structural-optical model is that it provides essential information needed in most advanced treatments of radiative transfer in sea ice. It thus opens the way to enhanced utilization of transmission and reflection data for monitoring the state of the arctic ice pack and associated biological activity. We also expect that the Monte Carlo model will be a powerful tool not only for the design of optical experiments and the analysis of radiometric data from 3-dimensional media, but also for developing and testing optical parameterizations that can be used in more conventional radiative transfer models.

TRANSITIONS

We expect to complete our laboratory experiments and model development in the coming few months. At that time we intend to focus our attention on summer field measurements that will be carried out as part of the SHEBA (Surface HEat Budget of the Arctic Ocean) Experiment in the Beaufort Sea. Knowledge and theoretical tools developed during this project will play a key role in the analysis of SHEBA data. In return, we expect that SHEBA data will provide a final test for the structural-optical model.

RELATED PROJECTS

This project will be merged with an ONR sponsored SHEBA project, "Experimental and Theoretical Studies of Ice-Albedo Feedback Processes in the Arctic Basin," that is being carried out jointly by investigators at the University of Washington (Maykut and Grenfell, N00014-97-10765) and at the Army Cold Regions Research and Engineering Laboratory (Perovich et al., N00014-97-MP-30046).

PUBLICATIONS

Light, B., H. Eicken, G.A. Maykut and T.C. Grenfell, A model study of the effect of particulates on the albedo of sea ice, in *Current Problems in Atmospheric Radiation*, W.L. Smith and K. Stamnes, ed., pp. 11-14, Deepak Publishing, Hampton, VA, 1997.

Light, B., H. Eicken, G.A. Maykut and T.C. Grenfell, The effect of included particulates on the optical properties of sea ice, *J. Geophys. Res.* (submitted)